Use of Acoustic Emission Analysis to Evaluate the Self-Healing Capability of Concrete

K. Van Tittelboom, N. De Belie, F. Lehmann and C.U. Grosse

Abstract It has been estimated that, in Europe, 50% of the annual construction budget is spent on refurbishment and remediation of the existing structures [1]. Therefore, self-healing of concrete structures, which are very sensitive to cracking, would be highly desirable. In this research, encapsulated healing agents were embedded in the concrete matrix in order to obtain self-healing properties. Upon crack appearance, the capsules break and the healing agent is released, resulting in crack repair. The efficiency of this crack healing technique was evaluated by using acoustic emission (AE) analysis. Breakage of the capsules was proven as events with an energy higher than the energy related to concrete cracking were noticed. Upon reloading of beams with untreated cracks, fewer emissions were detected compared to beams with healed cracks. From this study it was shown that AE is a suitable technique to evaluate self-healing of cracks in concrete.

Keywords Acoustic emission analysis • Concrete • Cracking • Polyurethane • Self-healing

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Introduction

Concrete is used world-wide as construction material because of its excellent mechanical properties and relatively low cost. The only drawback is that concrete easily cracks because of the limited tensile strength. These cracks do not only cause high repair costs, they also endanger the durability of the structure. Aggressive substances may enter the cracks and cause concrete degradation. Due to this, cracks may grow. When the reinforcement is exposed to the environment, corrosion may originate and finally the structure may fail. Therefore, immediate and autonomous crack repair is strived for. Concrete already exhibits some natural self-healing properties as unreacted cement grains may react when coming into contact with water entering the crack [2]. This is one of the reasons why old concrete structures like the Roman Pantheon are still existing. However as 1 tonne of CO_2 is emitted during the production of 1 tonne of cement, nowadays, the dosage of cement in concrete is adapted. Due to the former cause and due to the fact that much finer cements are used, less unreacted cement is available now. Besides, the natural healing mechanism is limited to narrow cracks and is unpredictable. Therefore, research is done to improve the crack healing efficiency by encapsulating healing agents inside the concrete matrix [3, 4]. Granger et al. [5] made use of acoustic emission (AE) analysis to evaluate the natural crack healing efficiency of concrete. The promising results found by Granger et al. were the incentive to use AE in order to evaluate the crack healing ability of concrete with encapsulated healing agents.

Materials and Methods

Preparation of the specimens

Ceramic tubes, with an inner diameter of approximately 3 mm and a length of 100 mm, were used to carry the healing agent. A commercially available polyurethane-based healing agent was used to seal the cracks. This healing agent consists of two compounds, one compound is a prepolymer of polyurethane that starts foaming in moist surroundings. The second compound is an accelerator which shortens the reaction time. Half of the tubes was filled with the prepolymer and the other half was filled with a mixture of accelerator and water.

In order to protect the brittle tubes from breakage during preparation of the concrete beams, they were embedded inside mortar bars with dimensions of 20 mm x 20 mm x 120 mm. Mortar was made up of sand 0/2 (1530 kg/m^3), cement CEM I 52.5 N (510 kg/m^3) and water (255 kg/m^3). In each mortar bar, tubes filled with the prepolymer and the accelerator were positioned next to each other.

Moulds with dimensions of 500 mm x 110 mm x 50 mm were used for preparation of four series of concrete beams. Concrete was composed of sand 0/4 (670 kg/m^3), aggregates 2/8 (490 kg/m^3), aggregates 8/16 (790 kg/m^3), cement CEM I 52.5 N

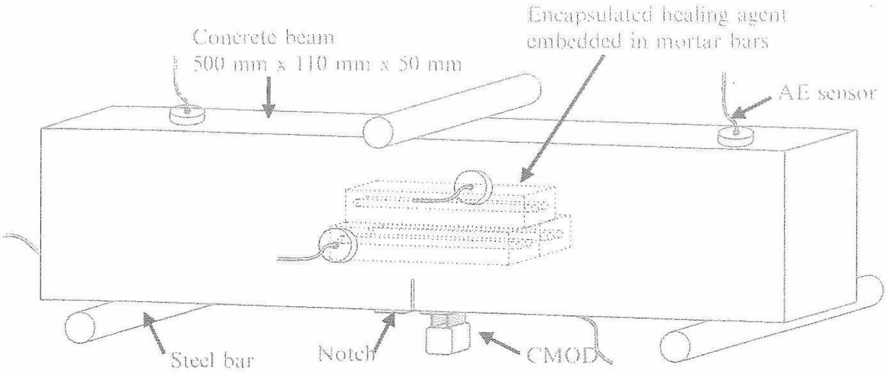

Fig. 1 Setup of the experiment showing the position of the protected ceramic tubes inside the concrete beam together with the position of some of the sensors

'REF', specimens of which cracks were treated manually with epoxy 'EPO' or polyurethane 'PUR'), standard concrete beams were prepared. When beams of the last test series (self-healing specimens with encapsulated polyurethane 'SHC_PUR') were made, the moulds were filled in several layers and the mortar bars, containing the tubular capsules, were positioned inside the beams. After casting, all moulds were placed in an air-conditioned room with a temperature of 20±2 °C and a relative humidity of 90±10 % for a period of 24 hours. After demoulding, the specimens were placed in the same room for at least 27 days. Finally, a 20 mm deep notch was sawn at the bottom, in the middle of the specimens. The design of the concrete beams with self-healing properties is shown in Fig. 1.

Creation of controlled cracks

Cracks were created by means of a crack width controlled three-point-bending test. The crack width was measured by means of a Crack Mouth Opening Displacement (CMOD) sensor, placed between two steel plates stuck on each side of the notch. The crack width was increased with a velocity of 0.5 μm/sec until a width of 300 μm was reached. At that point, the beam was unloaded giving cause to a residual crack width of about 225 μm.

During crack formation all beams were instrumented with an AE system. The instrumentation consisted of eight piezoelectric transducers (see Fig. 1) with a nominal diameter of 25 mm and a relatively flat frequency response below 1 MHz. The transducers were coupled to the concrete beams by means of hot glue. The detected signals were amplified with 54 dB gain amplifiers. The frequency range of the acquisition of wave forms was set from 1 kHz to 1 MHz. The slew rate trigger was set to 0.08 V/μs and an input range of ±5 V was chosen. The software

Crack healing

For beams with self-healing properties, the healing mechanism was activated upon crack appearance. During crack formation, the tubes broke and both components of the healing agent were released into the crack due to capillary forces. When both components made contact, a polymerization reaction was triggered and the crack was healed. Cracks of the samples belonging to the test series 'PUR' and 'EPO' were treated immediately after crack formation with, respectively, polyurethane and epoxy. In the former case, the prepolymer was mixed with water and accelerator in the same proportions as encapsulated in the tubes, otherwise, both components of the epoxy resin were mixed according to the instructions of the provider. The cracked concrete beams were turned upside down and at the position of the crack, the sides of the beam were covered with tape. Then, the mixture was injected into the crack by means of a syringe with a needle. Injection was stopped when the crack appeared to be completely filled with healing agent.

Evaluation of the crack healing efficiency

24 hours after crack repair, the specimens were reloaded in three-point-bending in order to test the crack healing efficiency. During this reloading cycle sensors were coupled again in the same position as during crack creation.

Results and Discussion

The recorded events were filtered using the software All2SDF. A bandpass filter with a rectangular window with a lower and higher cut off frequency of 35 and 300 kHz, respectively, was used. For each event the according energy was determined and events were subdivided into seven classes based on their energy. Localization of the events was done based on the filtered signals and using the program PolarAE. The Hinckley criterion was used for automatic detection of the onset time. Subsequently, a selection of the events was made based on their energy (>1) and the number of channels used for localization (>5). All further analyses were performed onto these selected events.

In Fig. 2 the loading curves during crack creation (light grey) and reloading (dark grey) are displayed together with the emitted events (also light and dark grey). Each event is represented by means of a dot and based on their energy class they are represented in different levels.

Only for beams with encapsulated healing agent events from the highest energy level were noticed. It was thought that these events were caused by breakage of the embedded tubes as they were accompanied by drops in load and audible

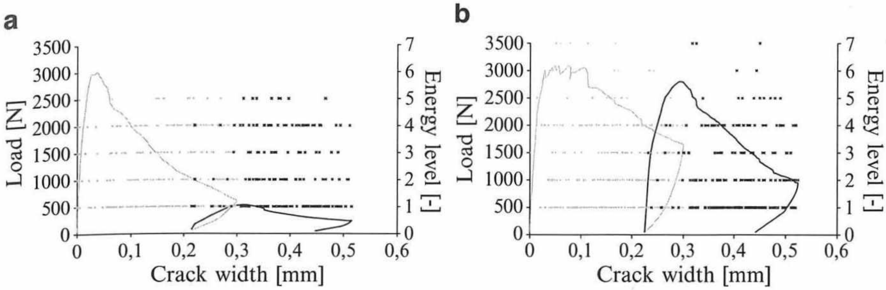

Fig. 2 Loading curve obtained during crack creation and reloading for an untreated (**a**) and autonomously healed (**b**) crack. The captured events are represented by means of dots depending on their energy level

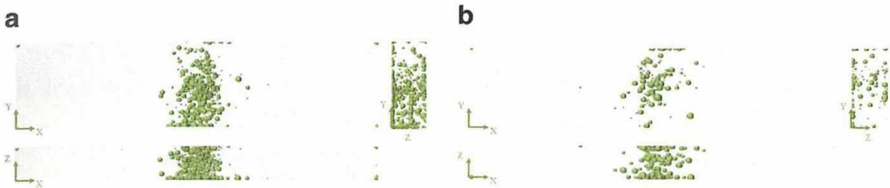

Fig. 3 Localization of the events during crack creation (**a**) and reloading (**b**), the sphere size is related to the released energy class, test specimen belonging to the test series REF

'pop' sounds. Also during reloading, the energy released for autonomously healed cracks is higher than for the other test series. This could be explained by the fact that some additional tubes broke upon reloading. This was also heard during the test and seen from the reloading curves. Due to the second release of healing agent, a second healing action may occur, as already noticed in previous experiments [6].

The position of the events was drawn on the XY, XZ and YZ plane of the beams. This was done for the loading and reloading cycle. For events with a bigger energy and thus belonging into a higher energy class bigger dots were used. It is seen in Fig. 3 that upon reloading of the beams less events were recorded. However, this is not only true for the reference beams but also for the beams from which the cracks were healed. While it was expected that more events would be captured upon reloading of the beams with healed cracks, this was not seen from these results.

The findings mentioned above could be explained by the fact that upon reloading of the beams different phases could be distinguished. In the first phase the crack just reopens for the reference beams or cracks appear in the healing agent in case of beams with healed cracks. When the crack opening, which was reached during crack creation, is reached again, new cracks start to form in the concrete matrix. This is the start of the second phase. The third phase corresponds to the moment when the adjusted crack width is reached, loading is stopped and the crack width decreases. As the second and the third phase are equal for all test series, and quite

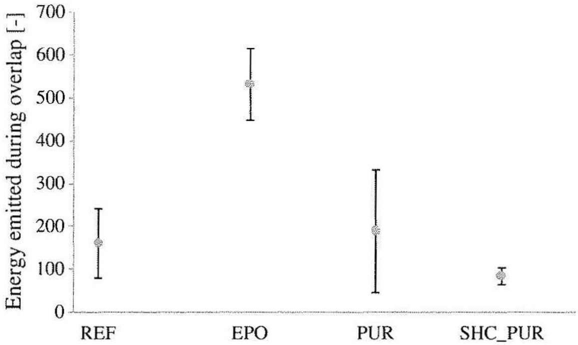

Fig. 4 Energy emitted during the first phase of reloading (this means during the overlap of pre-cracking and reloading); dots represent the mean value, error bars represent the standard error (n=5)

some events are produced during the second phase, these events may mask the differences between the first phases of the different test series.

Therefore the energy of all events which occurred during the first phase was cumulated. A significant difference was noted between the energy released for cracks manually healed with epoxy and the other test series (Fig. 4). For the specimens where the cracks were healed with polyurethane (manually or automatically) no significant difference was noted; however, from the regain in mechanical properties [7] it was seen that these cracks were healed. That no significant difference is seen by means of AE can be explained by the fact that crack formation into the polyurethane foam does not cause events with high energy.

Conclusions

From this study we can conclude that breakage of the tubes of self-healing concrete can be proven by means of AE measurements. Although self healing of cracks using PU as healing agent is not proven from the AE measurements presented in this paper, crack healing is proven in the case epoxy resin is used as healing agent. The possibility to use AE as indicator for self-healing of cracks, will therefore depend on the mechanical properties of the healing agent used.

References

[1] Cailleux, E. and Pollet, V. (2009), *Investigations on the development of self-healing properties in protective coatings for concrete and repair mortars*, Proceedings of the 2nd International Conference on Self Healing Materials, pp. 120.

[2] Neville, A. (2002, *Autogenous healing – A concrete miracle?*, Concrete International 24 (11), pp. 76–82.

[3] Li, V.C., Lim, Y.M. and Chan, Y-W. (1998), *Feasibility study of a passive smart self-healing cementitious composite*, Composites Part B: Engineering 29(6), pp. 819–827.

[4] Dry, C. and Corsaw, M. (2003), *A comparison of bending strength between adhesive and steel reinforced concrete with steel only reinforced concrete*, Cement and Concrete Research 33(11), pp. 1723–1727.

[5] Granger, S., Loukili, A., Pijaudier-Cabot, G. and Chanvillard, G. (2007), *Experimental characterization of the self-healing of cracks in an ultra high performance cementitious material: Mechanical tests and acoustic emission analysis*, Cement and Concrete Research 37(4), pp. 519–527.

[6] Van Tittelboom, K., De Belie, N., Van Loo, D. and Jacobs, P., *Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent*, submitted.

[7] Van Tittelboom, K., De Belie, N., Lehmann, F. and Grosse, C. (2010), *Towards durable concrete that repairs cracks autonomously*, Proceedings of International RILEM Conference on Use of Superabsorbent Polymers and Other New Additives in Concrete, pp. 285–292.